Phase Transitions and Crystalline Structures in Neutron Star Cores [1]

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This paper presents a detailed study of the crystalline structure that is expected to occur in the coexistence phase of quark and hadronic matter in any fully equilibrated system such as a degenerate star. Indeed, spatial structure such as we have described will occur in the mixed phase region of any equilibrated system that has more than one conserved charge (or independent component) of which one is the electric charge (giving rise to a long-range interaction). The physical reasons underlying the structured phase in neutron stars was explained. For hypothetical compact hybrid stars, stars with a neutron star exterior, and a quark matter or mixed phase interior, we have computed the varying geometrical structures and radial extent that they occupy as a function of stellar mass in two models that span the range in uncertainty in nuclear matter properties.

We find extreme sensitivity of the spatial structure to stellar mass. The pattern is the following: For stars near the limiting mass, the interior few kilometers is a quark gas surrounded by a few kilometer thick crystalline region having all geometrical forms from hadronic drops immersed in quark matter at the inner edge of the mixed phase, to quark drops at the outer edge, with other forms, rods and slabs between. Exterior to the crystalline phases is the liquid phase of nuclear matter which in turn is enclosed by a thin metallic crust. For Stars only slightly less massive, the pure quark phase is absent and the crystalline mixed phase extends to the center of the star. The radial extent of the crystalline structure shrinks with decreasing mass until the star is purely a neutron star. However, according to our calculations, the mixed phase is absent only for very low-mass stars, below about $M_{\odot}$.

It is almost certain that a solid region in a pulsar will play a role in the period glitch phenomenon, which is highly individualistic from one pulsar to another. This is expected for at least two reasons. All solid regions will be subject to stresses as a pulsar spins down and the centrifugal force decreases. Solid regions alone can be the site of episodic relief of stresses that cause sudden changes in the moment of inertia and hence 'glitches' in the rotational frequency.

Previously the only expected region of solid material was the thin crust. Here we find also a deep interior solid region of thickness of a few kilometers, which varies sensitively from one star to another according to the stellar mass. Moreover we can anticipate that the region occupied by the inner solid region and the boundaries between the different spatial geometries will vary through the life of a given pulsar as it spins down and its density profile changes. Moreover, since the compensating charge density of both phases in equilibrium are non-zero and vary as the proportion of the phases and therefore with depth in the star, the superfluid properties will be different from those expected for a charge *neutral* hadronic fluid. We tentatively suggest that the individualist behavior of pulsars with respect to their glitch characteristics arises from the extreme sensitivity of the crystalline structure on stellar mass both for reasons of its being a solid as well as the different superconducting properties expected for the coexistence phase. In addition, the dependence of glitch activity on pulsar age may be understood in terms of the evolution of the crystalline region with changing angular velocity. These are speculative associations between pulsar glitch behavior and the interior structure which seem plausible and worth pursuing.

[1] N. K. Glendenning, Physics Reports **342** (2001).